ENGINEERING PROBLEMS OF HIGH-SPEED FLIGHT

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Today as never before the survival of the free world and the maintenance of peace requires superiority in the performance and military effectiveness of our aircraft and missiles. A new sense of urgency must pervade the thinking and actions of research scientists, aircraft engineers, industrial executives, and military leaders comprising our aeronautical team. Never in the history of aeronautics have there been so many fruitful ideas to be explored by research. Never has there been a greater need for exploitation of those ideas, lest our enemies do so first.

Since the end of World War II, great advances have been made in aeronautics. Our research airplanes, once they had been flown to dispel the myth of the sound barrier, penetrated deeply into the supersonic range. The Bell X-1A built here in Buffalo has reached a Mach number of 2.5, the technical jargon for a speed 2-1/2 times the speed of sound.

America's aircraft manufacturers, using information developed in the nation's aeronautical research laboratories and proven by the research airplanes in flight, have designed and built tactical faster-than-sound aircraft and now are beginning to make deliveries to our Air Force and Navy. Within recent weeks, the Air Force permitted disclosure of a new fighter aircraft, the XF-101, capable of range and speed beyond the performance of previously announced models. This airplane has two jet engines with a total thrust of

20,000 pounds--as much effective power as that produced by six big Diesel locomotives. This airplane weighs about 40,000 pounds--about five times as much as the P-39 Airacobras and P-40 Kittyhawks which Bell and Curtiss built by the thousand during World War II. Other aspects of this new airplane are equally impressive--the electronic gear, enough to rival a television station; the new structural techniques employed. I could go on, but I believe the point is clear; today's military airplane is capable of supersonic performance, but it has become, in all its parts, fantastically complex, presenting engineering problems of a new order of complexity.

The arsenal of military weapons now includes guided missiles as well as aircraft. We have so accelerated their development that several are currently in service use. There is no sign that we are nearing the end of spectacular accomplishment in either aircraft or guided missiles.

However, the task of America's aircraft industry to create designs which will meet the operational and performance requirements of the military services remains gigantic. In addition to the higher flight speeds implicit in future performance goals, our aircraft must climb faster to higher altitudes, and carry larger loads to greater distances. Even at supersonic speeds, they must be maneuverable, and their qualities of stability and control must permit satisfactory operation by their pilots on the assigned mission. By their design and construction, they must be capable of avoiding or withstanding the perils of flutter, buffeting, and aerodynamic heating.

All this must be done as economically as possible as measured by initial investment of materials and labor and by operating cost.

The design of aircraft and missiles remains an art practiced by individuals or groups of individuals in a design team. They must have general knowledge of many fields, and they must possess the ability to synthesize information from many sources. They must be prepared to face and solve many engineering problems. Whereas research advances knowledge by isolation of limited aspects of development problems which are analyzed by specialists working in specific fields, the designer of an airplane or missile must solve all of the many problems in a single integrated prototype.

There has been a steady evolution in the art of design and in the kind and complexity of the associated engineering problems from the days of the first airplane to the present day.

In 1903, hardly 50 years ago, Orville and Wilbur Wright conceived, designed and built the first airplane to accomplish controlled, powered flight. They also designed and built the engine to power their "Wright Flyer." For a number of years following that first successful flight, it was possible for any individual to learn and know all there was to be known about aeronautics and airplane design. If equipped with the requisite creative powers, he might become a successful designer.

The situation soon changed.

Today, it is very difficult to discover the designer of one of our modern airplanes. It is the product of a large organization of many specialists of many types; it is the product of a team. No member of the team has complete knowledge of the final product in all its detail. When you examine today's 40,000-pound supersonic fighter, you do indeed wonder how any one man could have invented or designed it. Of course, no one man did or could. Its development rests on the contributions of many men in the past and of many men now living.

A useful airplane like any other accomplishment of the human race is preceded by creative activity in the invisible world of some human mind. The pathway from vision to accomplishment is sometimes long and arduous.

The vision of the designer is guided today not only by the experience and accomplishments of the past but also by the specialized and somewhat artificial type of experience known as scientific research. Modern science seeks to know and understand the laws of Nature--how air flows around bodies; what forces, pressures, and loads are exerted on bodies moving through the air; how materials and structures behave under load. Such knowledge is the secure foundation on which all engineering accomplishment rests.

The feeding of the results of the experiences of the research worker into the mind of the engineer does not, however, make him a creative designer. The distillation of the discoveries of other men into an engineering handbook may provide sufficient basis for the training of engineers in some fields. But in aeronautics, economy of materials and refinement of design are of great importance; in aeronautical development, there is little room for the handbook engineer.

Likewise, mere training in the knowledge and techniques of the aeronautical sciences will not make a good member of an aircraft design team. The art of inventive application must also be mastered, the art of finding new means to old ends, skill in finding new combinations of old elements. Problems must be met not only with correct scientific and technical knowledge but also with ingenuity. Creative activity within the mind of the aircraft designer is the first step along the pathway toward the practical realization of a successful airplane.

The next step is to send out exploring parties, to make forays to verify or modify the intended course. This is the activity of applied research. The questions now are asked of Nature. You recall Boss Kettering's approach of asking the Diesel engine rather than a consulting engineer whether a given design of piston was good or not. The theoretical and conceptual ideas must be given the acid test of actual trial. If the theory proves wrong, if one approach does not make progress towards the goal, the intelligent engineer will seek a new theory or a new approach.

In aeronautical development we find need for a great deal of applied research. Some is of a very specific nature directed to limited objectives. Some is of a very general nature directed to broad objectives.

The result of all this activity is to establish confidence that the vision is a realizable one, that the foreseen problems can be solved. The unforeseen problems are another and later story.

The scene now reverts to the immaterial sphere of the mind. The problem now is to sharpen the vision to an integrated and coordinated design. Necessary compromises between conflicting requirements must be made. The solution must be consistent with demonstrated possibilities of achievement.

The designer is a creative artist like the architect, who with a given site on a rocky hillside, a given family with living habits and needs known to him, and a certain supply of available materials plans a structure which most harmoniously satisfies the given conditions. Or, the designer is like the composer of a great symphony, who knows the characteristics and capabilities of all of the different instruments and must write the score for all. The result is to be a unified and integrated composition. The success or failure is in the composer's hands and is decided before the orchestra plays a single note.

The symphony orchestra now takes over from the composer; the builder from the architect; the production engineers and artisans from the airplane designer. Their job is to make the vision come true, to translate the score into music, the plans into homes, the acres of blueprints into a structure of aluminum, steel and plastic--an airplane.

At every step the same cycle of mental-physical activity is repeated. Each accomplishment is preconceived in the mind of man, and the more creative, the more inventive, the more experienced, and the more intelligent the man who conceives and plans, the more advanced and the more suitable to its purpose is the resulting product.

Now come the unforeseen problems as the user takes over. The new airplane is born not to be set on a pedestal to be admired for its beauty, for the complexity of its construction, or for its cost. It was made to serve a purpose; it is a tool to accomplish the purposes of man, in defending him and his possessions, or in attacking his enemies.

The prototype moves out of the factory. In every way, short of actual flight, it is checked in operation. Only then does it roll to the end of the runway, for takeoff on its maiden flight. It is rained on, hailed on, frozen and scorched, pounded by gusts, and jolted by hard landings. The process of evaluation has hardly commenced before further development to overcome shortcomings begins. This is the life cycle of a new airplane.

I have noted the distinction between the solo effort of yesterday's inventor and the symphony of today's team. And yet it seems to me that we have come to an era in which even this latter concept is inadequate. After all, the score of the symphony can be broken down into separate scores for each instrument. A coordination is necessary as regards time, melody, and harmony, but this can readily be accomplished because details of the score for each instrument can be worked out once the general structure of the composition has been established. Too, the scoring of the symphony implies little interference or interaction.

Prior to World War II, hardly 15 years ago, the design problems of an airplane could be readily broken down into aerodynamic problems, power plant problems, structural problems, electrical problems, hydraulic problems, and so on. Each group could work out the optimum solution from its own specialized point of view with comparatively little interference. The most necessary coordination was a purely dimensional one. Space had to be available as required. Mating parts had to fit and operate without mechanical interference. There were, of course, a few problems of a different nature such as the effect of the propeller slipstream on the stability and control of the airplane. This problem did require consideration and optimization of the mutual effects by the propeller and stability groups. Similarly, the drag associated with cooling required joint study by the power plant and aerodynamic groups.

As speeds increased, the aerodynamicist began to complain of the many crude excrescences demanded by the electronics group for radio and radar antennae. As structural design was refined, the mutual effects of aerodynamic loads on structural deflection and of structural deflection on aerodynamic loads introduced borderline problems of flutter and aeroelasticity.

Today's power plants swallow so much air that the separation of thrust from drag becomes almost a matter of definition. The interaction between power plant and flow around the airframe is so great that experiments on the whole configuration, with operation of the power plant included or simulated, become almost indispensable. High speeds show up the limitations of the human body as a servomechanism for responding to stimuli, and a whole new science of automatic control of aircraft is being born.

In all of these cases, the mutual interactions are large and a functional coordination is required. New methods for systems analysis must be devised. Complexities of a new type are introduced. The problem differs from one which involves merely the pyramiding of a large number of similar elements, such as the builder does when he expands from putting up single-family houses to erection of a large multi-family apartment structure. There, the principal difference is in the number of bricks and workmen required.

In the past, the building of a large airplane differed from that of building a small one only in that many more people were required to do the detail design of many more joints and pieces. The building of a modern high-speed airplane or missile today requires a highly developed concept of team activity and functional coordination. The team itself must include more kinds of specialists with knowledge of more scientific fields.

The apparent slowness of guided missile development stems, I believe, from these new requirements. The teams had to be assembled and the team members had to learn to work together. They had to learn the nature of the intricate problems and methods for their solution by actual solution. They had to devise new methods of system analysis and how to overcome unforeseen problems.

Development of the art of airplane and missile design to its present state would have been impossible without a parallel advance in scientific research, and the utilization of the research results by the designer. Research has also progressed from the unrelated investigations of a comparatively few individuals working on subjects which interested them. Now we have the organized effort of large groups on programs whose goals are set by the joint thinking of university scientists, research staff, aircraft designers and aircraft users. It is this collaboration of scientist, designer, and user which has made present-day aeronautical research so fruitful and has permitted so rapid a rate of progress.

Finally, of course, there has had to come an integration of the efforts of the research scientist and the designer to a degree undreamed of in recent years. We who are engaged in research are pleased by the manner in which our collaboration with the design teams responsible for many current prototype aircraft is being recognized by the members of those design teams as an important element in the success of their new airplanes. And, today, the performance of the new prototypes is proof-testing agreeably the accuracy of predictions drawn from the wind tunnel and other research data. Conversely, the research workers of today have a keener understanding of the designer's task. Perhaps, also, they have a more intimate awareness of his responsibilities in the aircraft development process.

Before us lie many engineering problems, too numerous to deal with in detail in this paper. A few examples will illustrate their complexity and the interplay between aeronautical engineering and basic and applied science. The same collaboration of scientist, engineer, and designer which has brought us so far in a half century can solve these new problems.

Many of the major problems of the aircraft of the future are old problems in new dress. The first technical report of the National Advisory Committee for Aeronautics, written in 1915 by Dr. J. C. Hunsaker, present NACA Chairman, dealt with the problem of the stability of an airplane in free flight. The then current high-speed military airplane was the Curtiss JN2 with a maximum speed of about 85 miles per hour and a minimum speed of about 43 miles per hour. Dr. Hunsaker concluded that "while this aeroplane appears to be very stable at high speeds, it is frankly unstable at speeds below 47 miles per hour..... The importance of this demonstrated instability at low speeds should be appreciated in view of recent accidents with military aeroplanes when operated at slow speeds."

The problems of stability and control of current and future aircraft are describable in the same conceptual framework that G. H. Bryan clothed in mathematical language in 1911, the same framework which Hunsaker applied in NACA Report No. 1. There are, however, great changes in the superstructure, in what Bryan described as the approximations to the air pressures to which the planes and other parts of the machine are subjected. For our future airplanes we must assure stability not at speeds of 40 to 90 miles per hour, but at speeds extending from 100 to 1000 miles per hour or more. These speeds extend from the subsonic through the transonic well into the supersonic range with their differing "approximations to the air pressure on the planes and other parts." Higher altitude also has a detrimental effect on stability because of the lower density of the air.

The sharp rise in speed and altitude has caused a significant deterioration in dynamic stability. For example, when the steady flight of a modern transport airplane is disturbed by a side gust, the resulting lateral oscillation quickly dies out. In a supersonic fighter, the same gust is more likely to cause a persistent oscillation which damps out more slowly. This different behavior is attributable to many factors. The new configurations are radically different. Their wings are thin and are either sweptback or of small span. The weight is distributed mainly along the fuselage axis. The rotors of jet engines constitute powerful gyroscopes which couple the lateral and longitudinal motions. At supersonic speed the effectiveness of stabilizing surfaces decreases. At a given angle they give a smaller lift coefficient. A large effort, both theoretical and experimental, is required to determine the numerous aerodynamic parameters which are needed to compute the disturbed motions of an airplane over its wide range of operating speeds and maneuvers. In many cases the parameters vary in non-linear fashion with angle or speed necessitating new methods of attack.

The stability problem is one of designing the airplane to possess satisfactory oscillation characteristics without compromising seriously other fundamental performance requirements. It is becoming apparent that over the range of flight speeds and altitudes new possible, purely aerodynamic means may not suffice. Automatic stabilization is being used increasingly. For example, a suitably mounted gyro may be used to measure the airplane's directional motion, and transmit this information to a servomotor which moves the rudder so as to damp the motion quickly. Other more complex automatic control systems provide many possible methods of controlling aircraft response to disturbances or to assume complete control of the aircraft during maneuvers. For research purposes such systems have been applied to conventional fighters with adjustable controls to vary dynamic stability during flight. These variable-stability airplanes are used to simulate the characteristics of airplanes on the drawing board or to determine pilot's reactions to various degrees of stability.

In recent years new methods for the engineering analysis and design of dynamic systems have found fruitful application to the field of aircraft stability. The dynamics of the aircraft alone are expressed in terms of the frequency or transient response, which have been studied both in wind tunnels and in free flight.

A second example of an old phenomenon in new guise is flutter, which has resulted in the catastrophic destruction of aircraft from time to time since World War I. Flutter of a flag in the wind is a familiar phenomenon. As the structure becomes more rigid, the flutter speed increases. In flutter, bending or twisting oscillations of the structure or its parts increase in amplitude by absorbing energy from the air flow until failure occurs. The original Tacoma Narrows bridge was destroyed by flutter. The study of flutter requires knowledge of the many modes of vibration of complex structures and of the air forces resulting from the vibration.

Most early cases of flutter resulted from movements of the aileron or other control surface combined with twisting or bending of the wing or tail structure. Cure was obtained by balancing the control surface by adding mass ahead of the hinge line so that oscillations of the wing or tail did not cause the control surface to rotate. Today the flutter problem is more complex at the much faster speeds and with the thinner, heavier, and more flexible construction. Different patterns of flutter and different flutter speeds may be found for the same airplane as it climbs or dives from one altitude to another because of changing air density.

Some of the newer airplanes carry engines, fuel tanks, or rockets distributed along relatively flexible thin wings. The number of variables which must be considered is very large. In such cases tests on dynamically similar models have been found most useful. The advent of modern automatic digital computers has facilitated theoretical computations of structural and aerodynamic characteristics. Nevertheless design to avoid flutter is still an art rather than a science, although the design is supported by extensive engineering analysis.

A completely new series of engineering problems is imposed by the so-called "thermal barrier", a poor term because this barrier will succumb to bold engineering attack as did the sonic barrier. Meteors traveling through the air get so hot from air friction that their surfaces melt. At speeds which will be attained in future aircraft, aerodynamic heating will raise the temperature of the airplane to the point where presently used materials lose a large part of their strength. Even before this point is reached, aerodynamic heating produces thermal stresses in the structure, distorts the structure by unequal thermal expansion, or changes its stiffness. Such effects may induce a premature flutter.

The effects of aerodynamic heating may be ameliorated by the use of materials which withstand higher temperatures, by clever structural design to avoid high thermal stresses or harmful distortions, or by the use of refrigeration or insulation to maintain the structure at temperatures lower than that of the air near the surface.

The engineer has been provided by the research scientist with much design information but there are still many unknowns, some of a very fundamental nature. The temperatures attained depend markedly on the nature of the flow in the boundary layer, whether laminar or turbulent. Although we know in a general way how transition depends on Mach number, heat transfer, pressure gradient, free stream turbulence, surface roughness, and disturbances from shock waves, noise, and wakes of other bodies, we cannot predict its exact location with sufficient precision for optimum engineering design.

There are a great many other engineering problems of high-speed flight, some old ones grown more complex, and some totally new ones. Some lie in the field of aerodynamics, some in propulsion, some in materials, some in structures, some in electronics, some in aeromedicine. All of these can and will be solved if we can solve what is perhaps the most troublesome problem of all...... IF: -----

If each year we replenish the supply of workers technically trained in the many fields which contribute to the art and science of aeronautics. This year the engineering graduates from our technical schools will number somewhere between 20,000 and 25,000. In Russia, we are told, the number of technically trained in 1955 will be close to 100,000.

Obviously, if year in and year out, Russia is to give technical training to four times as many young men as we do, we cannot hope to maintain for long our present lead in aeronautics.

That, I submit, is the most serious of the problems of high-speed flight which confront us in America today.